(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
8 March 2001 (08.03.2001)

PCT

(10) International Publication Number
WO 01/15819 A1

(51) International Patent Classification[7]: B05D 3/06, 5/12, B32B 15/08, B23K 26/00

(21) International Application Number: PCT/US00/23835

(22) International Filing Date: 30 August 2000 (30.08.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/151,408 30 August 1999 (30.08.1999) US

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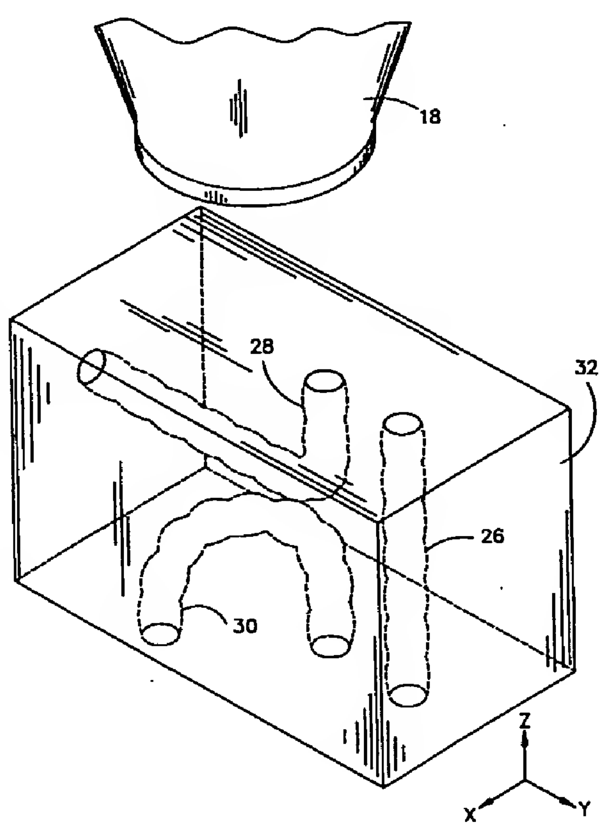
(81) Designated States (*national*): AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT,

[Continued on next page]

(54) Title: THREE-DIMENSIONAL ELECTRICAL INTERCONNECTS



(57) Abstract: Ultrafast laser pulses focused by lens or optics (18) are used to produce subsurface channels (26, 28, 30) in a variety of insulating materials (32), including silica, quartz, diamond, silicon, or other materials of interest to the electronics industry. These channels may be used as optical waveguides, and an electrical conductor may be introduced into the channels to provide electrically conducting interconnects or dual waveguides (optical/electrical). In a further embodiment, the coolant may be circulated within the subsurface channels to prevent heat buildup in electrical components.

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RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) **Designated States** *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
— *With international search report.*
— *Before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments.*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

TITLE:

THREE-DIMENSIONAL ELECTRICAL INTERCONNECTS

SPECIFICATION

BACKGROUND OF THE INVENTION

The present invention relates to the creation of subsurface channels in a substrate and, more particularly, to a method for creating subsurface channels within the bulk of a material using ultrashort laser pulses. The subsurface channels may be employed as optical waveguides or as electrically conducting interconnects when a conducting material is placed therein. In other aspects, the present invention relates to the subsurface channels and three-dimensional electrically conducting interconnects so produced and an apparatus for producing the same.

In recent research [1] using ultrashort pulse femtosecond lasers, optical waveguides 200 nm and smaller have been written inside various glasses such as synthetic silica, borosilicate, fluoride, and chalcogenide glasses with 800 nm, 120 fs, 1000 Hz mode-locked laser pulses. Three-dimensional optical storage inside transparent materials has also been demonstrated with micron and submicron spacings [2, 3, 4]. These unique capabilities are made possible by nanomachining methods using femtosecond laser pulses. Unlike the longer pulsed nanosecond lasers, new femtosecond lasers totally change the mechanisms of laser-matter interactions. One of the most important differences between nanosecond laser pulses and femtosecond laser pulses is that the breakdown threshold in materials using femtosecond pulses is very sharp since femtosecond pulses generate their own source of free electrons. These well defined thresholds allow femtosecond laser nanomachining to be performed with improved control and precision. In a recent article by Li and

Mourou [5], the sharp breakdown threshold is clearly demonstrated in fused silica. In producing the photo-induced changes in fused silica, a void region is produced surrounded by a region of high-density quartz. The index of refraction of these dense quartz regions has been observed to increase by 0.05-0.45. This change results in the possibility of using the femtosecond laser induced index of refraction changes/voids to optically write data in three dimensions, and to make subsurface channels or optical waveguide interconnects.

Due to the advantages associated with parallel processing, in addition to the inherent input/output bottlenecks that occur in existing processing architectures, many view three-dimensional electrical interconnects as the future of interconnect technology. However, the creation of these three-dimensional structures presents many technological challenges that must be addressed.

Conventional methods for producing multilayer channels and vias in substrates involve forming metallization patterns in layers of insulating and conducting materials and building up successive layers, with each layer requiring a relatively large number of steps, such as surface treatment and planarization, stamping, masking, patterning, etching, deposition, curing, and plating steps, and so forth. Thus, it would be desirable to provide a three dimensional electrical interconnect fabrication methods capable of forming three-dimensional interconnects in the bulk of a substrate directly without the need for layer-by layer building of the substrate to achieve multilevel electrical interconnects.

SUMMARY OF THE INVENTION

The present invention provides a method for creating three dimensional electrical interconnects and allows for the creation of high density electrical interconnects for integrated circuits and/or other electronic components. The method may be adapted for both on-chip electrical interconnections and chip-to-chip interconnections.

In one aspect, the present invention provides a method for forming one or more electrical interconnects in a substantially transparent insulating substrate comprising the steps of supporting the insulating substrate, defining the path or paths of the one or more electrical interconnects within the substrate, directing focused ultrashort laser pulses at the substrate to selectively deposit energy to produce a structural void at a sufficient number of points along the path or paths to create one or more continuous channels defining the path or paths of the one or more electrical interconnects

within the substrate, and introducing a conducting material within the at least one of the one or more continuous channels to form an electrically conducting path within the at least one of the one or more continuous channels.

In another aspect, the present invention provides an apparatus for machining one or more electrical interconnects in a substantially transparent insulating substrate, the apparatus comprising an ultrafast laser source, support means for operably securing a part to be machined, means for directing focused ultrashort laser pulses at the substrate to selectively deposit energy to produce a structural void at a sufficient number of points along the path or paths to create one or more continuous channels defining the path or paths of the one or more electrical interconnects within the substrate, and means for introducing a conducting material within the at least one of the one or more continuous channels to form an electrically conducting path within the at least one of the one or more continuous channels.

In yet another aspect, the present invention provides three dimensional electrically conducting interconnects produced by the methods according to the present invention.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention as claimed.

The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate an embodiment of the invention and together with the general description, serve to explain the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The detailed description of the invention may be best understood when read in reference to the accompanying drawings wherein:

FIG. 1 shows a schematic diagram of an apparatus for producing subsurface channels in accordance with the present invention;

FIG. 2 shows an exemplary nano-machining apparatus according to the present invention

FIG. 3 is a pictorial depiction illustrating three types of interconnects that may be produced.

DETAILED DESCRIPTION OF THE INVENTION

The present invention involves the use of ultrashort laser pulses to produce channels in an insulating substrate. Using this invention, it is possible to produce subsurface, submicron channels in an insulating medium. These channels may be used, for example, to provide electrically conducting interconnects, optical waveguides, optical/electrical dual waveguides, and cooling channels to provide heat removal from electrical components.

The three-dimensional electrical interconnects in accordance with the present invention may be formed within many different types of materials. In one embodiment, the substrate is substantially transparent, including silica, quartz, diamond, silicon, glass, or other materials that may be used for electronic devices. In another embodiment, the machining may be accomplished in non transparent, absorbing materials so long as the attenuation of the laser pulse energy is effectively small, i.e., wherein the sample to be machined is very thin or wherein the subsurface channels are sufficiently close to the surface.

The method of producing the electrically conducting interconnects in accordance with the present invention may be used to provide three-dimensional integrated circuit interconnects, three-dimensional circuit boards or wiring boards for integrated circuits and/or electronic components, electrical interconnections for integrated electrical components of an integrated circuit. As used herein, unless specifically stated otherwise, the term three-dimensional is used to describe the formation of the conducting pathways within the three-dimensional bulk of a solid material, rather than any specific spatial configuration of the conductive pathways themselves. For example, it is not necessary that the three-dimensional interconnects themselves, in accordance with the present invention, comprise conducting pathways that comprise a spatial configuration having an x-, y-, and z-directional component. Thus, for example, the conductive pathways formed in accordance with the present invention (1) may comprise unidirectional interconnects formed within the three-dimensional bulk of a substrate; (2) may comprise circuitry located within or predominantly within a single plane or level within the substrate; (3) may comprise multilevel circuitry located within or predominantly within a plurality of discrete planes or levels; or (4) circuitry located within the bulk of a three-dimensional substrate without restriction or confinement to a particular level or plane in the x-, y-, or z-direction, or which may otherwise be non-linear or multidimensional in configuration.

Referring to FIG. 1, there is shown a schematic diagram of an apparatus for producing subsurface channels in accordance with the present invention. The apparatus comprises a source of ultrashort laser pulses **10**. Any laser capable of generating pulses in the range of about 1 attosecond up to about 1000 femtoseconds may be employed. Such lasers are generally known in the art and are commercially available. Common examples include dye lasers with compressed pulse means. In a typical embodiment of the present invention, the femtosecond pulse laser energy emitter is an amplified Ti:sapphire femtosecond laser or a colliding pulse mode (CPM) laser. In a particularly preferred embodiment, an actively stabilized argon laser (Coherent Innova 306 Argon Laser) is used to pump the femtosecond laser to produce a very stable femtosecond pulse. See also, Murname et al., "The Recent Revolution in Femtosecond Lasers," *IEEE LEOS Newsletter*, August 1993, p. 17; Glanz, "Short-Pulse Lasers Deliver Terawatts on a Tabletop," *R&D Magazine*, April 1993, p. 54; and especially, Messenger, "Technology of Ultrafast Lasers and Electro-Optics Expands Rapidly," *Laser Focus World*, September 1993, p. 69. An overview of ultrafast laser sources is also described in commonly owned copending U.S. Patent Application Serial No. 08/193,371, filed February 7, 1994, which is incorporated herein by reference in its entirety.

The femtosecond laser pulses **12** produced by femtosecond laser source **10** may be delivered and focused into the bulk of the sample or substrate **14** via delivery means **16**, such as a mirror, and focusing optics **18**. It will be recognized that any means of delivering or steering the laser energy to the sample may be used, including prisms, mirrors, lenses, optical fibers, optical crystals, filters, and the like, and any arrangements and combinations thereof.

The directional control of the focused laser spot within the material in which the subsurface channels are written may be provided by moveable optics, a moveable sample holder or platform **20**, or both. In one embodiment, focusing lens **18** is moveable in the direction of laser pulse travel (herein after referred to as the z-direction). In this manner, channels to be written, or portions thereof, that are oriented in the z-direction may be performed by moving focusing lens **18**, or by employing a platform **20** that is translatable in the z-direction. The channel may be written from the lower surface **24** of substrate **14** towards the top surface **22** of substrate **14**, or alternatively, may be written from the top surface **22** toward the bottom surface **24**.

In one embodiment, all movement during the write process is in the direction of laser propagation. This method has the advantage of producing smaller diameter channels since self-

focusing of the laser beam is in the direction of travel. Straight interconnect 26 shown in FIG. 3 illustrates the type of interconnect channel that may readily be written wherein the relative motion between the substrate and the laser is along the path of the laser pulse.

Nonlinear channels may be produced by writing the channel in the direction of laser pulse travel by appropriate rotation of the substrate. Thus, creating a channel such as right angle interconnect 28 shown in FIG. 3 can be accomplished by moving along one axis, for example, the z-axis, and then rotating the substrate 32 by 90 degrees and continuing to write the subsurface channel. Alternatively, creating a channel such as right angle interconnect 28 shown in FIG. 3 can be accomplished by starting at one edge and producing a continuous channel, for example, by moving substrate 32 in the y-direction, and then moving the sample (or alternatively, the focusing optics) in the z-direction so that the channel turns 90 degrees and proceeds to the top of the sample. Although this method, i.e., wherein the substrate is moved in the x- and/or y-direction, is not likely to produce as small a diameter channel since self focusing of the laser beam is no longer in the direction of travel, it obviates difficulties associated with entering a sample from multiple faces which requires a high degree of positional accuracy.

As stated above, the diameter of the channels may be smaller than the beam spot size due to self focusing. The channel diameters may range from several nanometers up to several microns, or greater. A preferred range of diameters is from about 10 nanometers to about several hundred nanometers. It will be recognized that larger channels, such as channels greater than one micron in diameter, may be produced using several passes over the path defining the channel to be produced, or the laser can otherwise be directed over a larger volume during a single pass. Where the size of the channel desired to be produced is larger than the voids produced by the laser pulses, it will be recognized that the method according to the present invention may be used to produce a channel having a desired cross-sectional geometry, in addition to the typical generally circular channels, including rectangular or other shapes that may be desirable in designing a waveguide.

Also depicted in FIG. 3 is a curved interconnect 30 which may be produced by moving the sample along the path of desired interconnect shape, by moving the focusing optics along the path of desired interconnect shape, or by coordinating the motion of both the sample and the focusing optics to produce the desired interconnect shape. In one embodiment, the x- and y-components of

movement necessary to produce the desired interconnect shape may be accomplished by moving the sample and movement of the focusing optics may be employed to furnish the z-component.

In a preferred embodiment, the channels formed in accordance with the present invention may be formed by synchronizing the movement of the sample and/or focusing optics with the ultrashort laser pulse source to produce the desired three-dimensional channels under automated or preprogrammed control.

Referring now to FIG. 2, there is shown an exemplary apparatus according to the present invention. The exemplary apparatus depicted is operable to embody the nano-machining method in accordance with the present invention, and further includes components that allow for the real-time monitoring of the femtosecond nano-machining. A Photonics Industries femtosecond laser system operating at a wavelength of 800 nm, pulse width of 150 fs, amplified pulse energy of 950 mJ, and operating at selectable frequencies up to 1 KHz may be used to create nanometer sized optical channels in materials of interest to the electronics industry. In the embodiment illustrated, a Ti:sapphire laser **40** is pumped by argon ion laser **42** and produces ultrashort pulses which are amplified by regenerative amplifier **44** pumped by Nd:YLF laser **46**. The output of the regenerative amplifier passes through neutral density filters **48**, zero-order half-wave plate **50**, and polarizer **52**. The femtosecond pulses will be coupled through a nano-machining apparatus shown schematically in FIG. 3, comprising x-y translator **20** and focusing optics **18**, which may be a microscope objective, for example, a 10x, 20x, 30x, 40x, etc., microscope objective. The entire system is mounted on a Newport Research Corporation optical vibration isolation table. Imaging lens **54** and color JVC camera **56** along with color monitor interfaced to computer **60** and synchronization circuitry **62** are used to observe the second harmonic emission (blue) intensity as the laser beam is either focused or moved to various positions. Illumination of the sample may be provided by fiber optic lamp **58**. The blue color intensity constantly changes as the femtosecond laser focus is moved in and out of the focal plane. Just at the threshold for material change (e.g., the material voids are produced) the blue intensity will disappear in a brilliant flash as the material is altered in the focal spot. Subsequent pulses focused at the same spot will not have the intense second harmonic generation. The result is a method that allows for the nano-machining process to be observed in real-time.

The femtosecond pulses focused through a 40x microscope objective 18 may be used to photowrite the waveguides or optically produced nanochannels in the bulk of the substrate, e.g., at specific three-dimensional subsurface planes. There are two preferred options contemplated that can be used in writing the subsurface channels. One option is to produce a channel along the path of the laser beam. This may be accomplished by moving the focus of the laser from the bottom of a chip to the top of the chip resulting in a continuous nanometer sized channel. This option is most likely to lead to the smallest size dimensions of the interconnects so produced. The other option is to locate the focal point at some position in the plane of the quartz and move the beam horizontally in two directions to produce an interconnect that could have any desired angle of turn as well as an in and out of plane direction. Because of self-focusing along the path of the beam channels in the x-y plane will most likely have a larger diameter. Again, the basic concept showing the two methods of generating interconnects is illustrated in FIG. 3. In regard to the minimum obtainable size of the subsurface defects, we note another important result of using femtosecond laser machining. For illumination conditions just at the material damage threshold, the size of the subsurface defects will actually be smaller than the diffraction limit of the optics being used. Obviously, the smallest channels can be produced by operating just at the material damage threshold. It is expected that z-(vertical) direction movement approaching about 10 nanometers will be required to produce a few nanometer diameter channel in the quartz. This is within the accuracy of available nanomovers (e.g., 10 nm per step) such as those used in the XYZ positioners of the existing nano-machining system at the University of Nebraska-Lincoln, Center for ElectroOptics.

The electrically conducting interconnects in accordance with the present invention may be produced by depositing a conducting material in the subsurface channels detailed above. The conducting material may be deposited in the channels by a number of methods. In one embodiment, surface tension forces may used to draw a conducting material into the channel produced in accordance with the present invention. The well-known classical expression for capillary rise in a tube is given by:

$$h = \frac{2T}{rdg}$$

where h is the height of fluid rise, T is the fluid surface tension, r is the radius of the

tube, d is the fluid density, and g is the gravitational force. Important physical properties for a variety of potential filler materials are given in Table 1.

TABLE 1

Material	Surface Tension (dynes/cm)	Specific Gravity	Melting Point (°C)*	Electrical Resistivity (μΩ-cm)
Copper (Cu)	1150	8.96	1084	1.7
Gallium (Ga)	704	5.91	29.8	17.4
Gold (Au)	1070	19.32	1063	2.4
Indium	515	7.31	156.6	8.37
Lead (Pb)	448	11.35	327.5	21
Mercury (Hg)	484	13.55	-38.9	96
Silver (Ag)	916	10.50	961	1.6
63-37 Sn-Pb Solder	481	8.52	183	15.0
Tin (Sn)	523	7.31	232	11.4
Zinc (Zn)	750	7.00	419.5	5.9

*Quartz Softening Point = 1665 °C

Low melting point conducting materials, such as gallium and common solder (63-37 Sn-Pb), are particularly useful, since both of these materials have low melting points and relatively high values for conductivity, making measurements on the electrical properties easier.

Another method of introducing a conducting material is to use a vacuum. For example, a vacuum may be applied to one or more sides of a substrate having nanochannels machined in accordance with the present invention, or to a portion of one or more sides thereof, to draw the molten conducting material into the channels. The use of a vacuum is particularly useful, for example, in cases where surface tension alone may not be sufficient to draw the material into channels.

In another embodiment chemical vapor deposition (CVD) processes, as are generally known to those persons skilled in the art, may be employed to introduce a conducting material into the channels produced in accordance with the present invention is chemical vapor deposition. In this manner, a conductive coating may be deposited on the surface of the channels, thus allowing the channels to simultaneously function as electrical wave guides (in the conductive layer or coating)

and optical waveguides. The metal may be deposited in the form of an inorganic salt or organometallic compound of the desired metal. It will be recognized that any conducting element, including high melting point metals, may be employed as the conductive material deposited by a chemical vapor deposition process, such as aluminum, tungsten, titanium, nickel, platinum, palladium, carbon, copper, gallium, gold, lead, silver, mercury, silver, tin, zinc, and so forth, or any mixtures or combinations thereof.

In addition to the three-dimensional electrical interconnects, the channels formed in accordance with the present invention may be used to overcome the problem of malfunction of integrated circuits due to heat buildup. The nano-channels formed in accordance with the present invention may be used as cooling channels for the cooling of integrated circuits, including three-dimensional or multi-layered chips. For example, in one embodiment, nano-channels are provided in multiple planes of an integrated circuit, and a coolant is circulated to absorb heat from within an integrated circuit to be released outside of the integrated circuit.

Although the present invention will be ideally suited to the manufacture of customized substrates, general purpose substrates can be produced in large quantity without prior knowledge of their intended final application, thereby reducing the cost of low volume, high diversity, production. Substrates can be personalized for quick turnaround by making the necessary modifications with further subsurface machining, reflowing the conductor or otherwise providing fusible links, and so forth.

The description above should not be construed as limiting the scope of the invention, but as merely providing illustrations to some of the presently preferred embodiments of this invention. In light of the above description and examples, various other modifications and variations will now become apparent to those skilled in the art without departing from the spirit and scope of the present invention as defined by the appended claims. Accordingly, the scope of the invention should be determined solely by the appended claims and their legal equivalents.

REFERENCES

All references cited herein are incorporated by reference in their entireties.

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CLAIMS

What is claimed is:

1. A method for forming one or more electrical interconnects in a substantially transparent insulating substrate, comprising the steps of:

(a) supporting the insulating substrate;

(b) defining the path or paths of said one or more electrical interconnects within said substrate;

(c) directing focused ultrashort laser pulses at said substrate to selectively deposit energy to produce a structural void at a sufficient number of points along said path or paths to create one or more continuous channels defining the path or paths of said one or more electrical interconnects within said substrate;

(d) introducing a conducting material within said at least one of said one or more continuous channels to form an electrically conducting path within said at least one of said one or more continuous channels.

2. The method of claim 1 wherein the conducting material is a metal.

3. The method of claim 1 wherein the conducting material is a metal selected from the group consisting of copper, gallium, gold, indium, lead, mercury, silver, tin-lead solder, tin, and zinc.

4. The method of claim 1 wherein the ultrashort laser pulse has a pulsewidth ranging from about 1 attosecond to about 1000 femtoseconds.

5. The method of claim 1 wherein the ultrashort laser pulse has a pulsewidth ranging from about 1 femtosecond to about 1000 femtoseconds.

6. The method of claim 1 wherein the conducting material substantially fills said at least one of said one or more continuous channels.

7. The method of claim 6 wherein the conducting material is introduced into said at least one of said one or more continuous channels by drawing the conducting material into said at least one of said one or more continuous channels using surface tension effects, pressure differentials, or both.

8. The method of claim 1 wherein the conducting material is introduced by depositing the conducting material on the surface of said at least one of said one or more continuous channels by chemical vapor deposition.

9. The method of claim 1 wherein energy is delivered to at least one of said at least one subsurface target points through the surface without causing damage at the surface of said substrate.

10. The method of claim 1 wherein at least one of said one or more continuous channels is formed by translating the substrate in a direction parallel to the direction of travel of the laser pulses.

11. The method of claim 1 wherein at least one of said one or more continuous channels is formed by translating the substrate in a direction perpindicular to the direction of travel of the laser pulses.

12. An electrical interconnect formed within a substantially transparent insulating substrate, comprising:

(a) one or more continuous channels formed within said substrate, said one or more continuous channel being formed by directing focused ultrashort laser pulses at said substrate to selectively deposit energy to produce a structural void at a sufficient number of points along said path or paths to create one or more continuous channels defining the path or paths of said one or more electrical interconnects within said substrate; and

(b) a conducting material within said at least one of said one or more continuous channels, said conducting material forming an electrically conducting path within said at least one of said one or more continuous channels.

13. The electrical interconnect of claim 12 wherein the conducting material is a metal.

14. The electrical interconnect of claim 12 wherein the conducting material is a metal selected from the group consisting of copper, gallium, gold, indium, lead, mercury, silver, tin-lead solder, tin, and zinc.

15. The electrical interconnect of claim 12 wherein the ultrashort laser pulse has a pulsewidth ranging from about 1 attosecond to about 1000 femtoseconds.

16. The electrical interconnect of claim 12 wherein the ultrashort laser pulse has a pulsewidth ranging from about 1 femtosecond to about 1000 femtoseconds.

17. The electrical interconnect of claim 12 wherein the conducting material substantially fills said at least one of said one or more continuous channels.

18. The electrical interconnect of claim 17 wherein the conducting material is introduced into said at least one of said one or more continuous channels by drawing the conducting material

into said at least one of said one or more continuous channels using surface tension effects, pressure differentials, or both.

19. The electrical interconnect of claim 12 wherein the conducting material is introduced by depositing the conducting material on the surface of said at least one of said one or more continuous channels by chemical vapor deposition.

20. The electrical interconnect of claim 12 wherein energy is delivered to at least one of said at least one subsurface target points through the surface without causing damage at the surface of said substrate.

21. The electrical interconnect of claim 12 wherein at least one of said one or more continuous channels is formed by translating the substrate in a direction parallel to the direction of travel of the laser pulses.

22. The electrical interconnect of claim 12 wherein at least one of said one or more continuous channels is formed by translating the substrate in a direction perpindicular to the direction of travel of the laser pulses.

23. An apparatus for machining one or more electrical interconnects in a substantially transparent insulating substrate, comprising:

(a) an ultrafast laser source;

(b) support means for operably securing a part to be machined;

(c) means for directing focused ultrashort laser pulses at said substrate to selectively deposit energy to produce a structural void at a sufficient number of points along said path or paths to create one or more continuous channels defining the path or paths of said one or more electrical interconnects within said substrate;

(d) means for introducing a conducting material within said at least one of said one or more continuous channels to form an electrically conducting path within said at least one of said one or more continuous channels.

24. The apparatus of claim 23 wherein said means for directing focused ultrashort laser pulses comprises focusing optics.

25. The apparatus of claim 23 wherein said means for directing focused ultrashort laser pulses comprises focusing optics, a moveable support for said substrate, or both.

26. A method for the simultaneous transmission of an electrical signal and an optical signal, comprising the steps of:

providing an optical/electrical interconnect formed within a substantially transparent insulating substrate, said optical/electrical interconnect comprising:

one or more continuous channels formed within said substrate, said one or more continuous channel being formed by directing focused ultrashort laser pulses at said substrate to selectively deposit energy to produce a structural void at a sufficient number of points along said path or paths to create one or more continuous channels defining the path or paths of said one or more electrical interconnects within said substrate; and

a conducting material within said at least one of said one or more continuous channels, said conducting material forming an electrically conducting path within said at least one of said one or more continuous channels, said conducting material further comprising a layer deposited on the surface of said at least one of said one or more continuous channels by chemical vapor deposition wherein a void remains interiorly of said deposited layer within said one or more continuous channels;

transmitting an electrical signal through said conducting material; and

transmitting an optical signal through said void.

28. A cooling system for an integrated circuit, comprising:

(a) a plurality of subsurface channels formed within the integrated circuit, said subsurface channels being formed by directing focused ultrashort laser pulses at said integrated circuit to selectively deposit energy to produce a structural void at a sufficient number of points along said path or paths to create said plurality of subsurface channels; and

(b) a coolant.

29. The cooling system of claim 28 further comprising a heat radiator located externally of said integrated circuit and coupled to said plurality of subsurface channels.

30. The cooling system of claim 28 wherein heat is removed from the integrated circuit by evaporation of the coolant within said subsurface channels and condensation of the coolant outside of said subsurface channels.

31. The cooling system of claim 28 wherein said integrated circuit is a three-dimensional integrated circuit.

32. A method of removing heat from an integrated circuit, comprising the steps of:

(a) providing a plurality of subsurface cooling channels within the integrated circuit, said subsurface channels being formed by directing focused ultrashort laser pulses at said integrated circuit to selectively deposit energy to produce a structural void at a sufficient number of points along said path or paths to create said plurality of subsurface channels; and

(b) circulating a coolant through said subsurface channels.

33. The method of claim 32 wherein the coolant is further circulated through a heat radiator, wherein said heat radiator is in fluid communication with said subsurface channels.

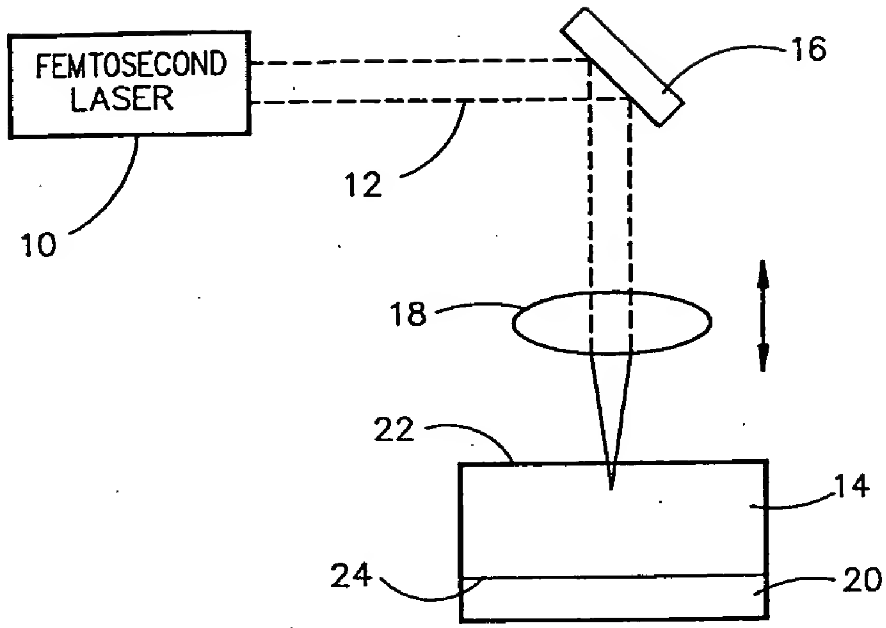
34. The method of claim 32 further comprising the steps of:

(c) evaporating at least some of the coolant within the subsurface channels;

(d) removing the evaporated coolant from the subsurface channels; and

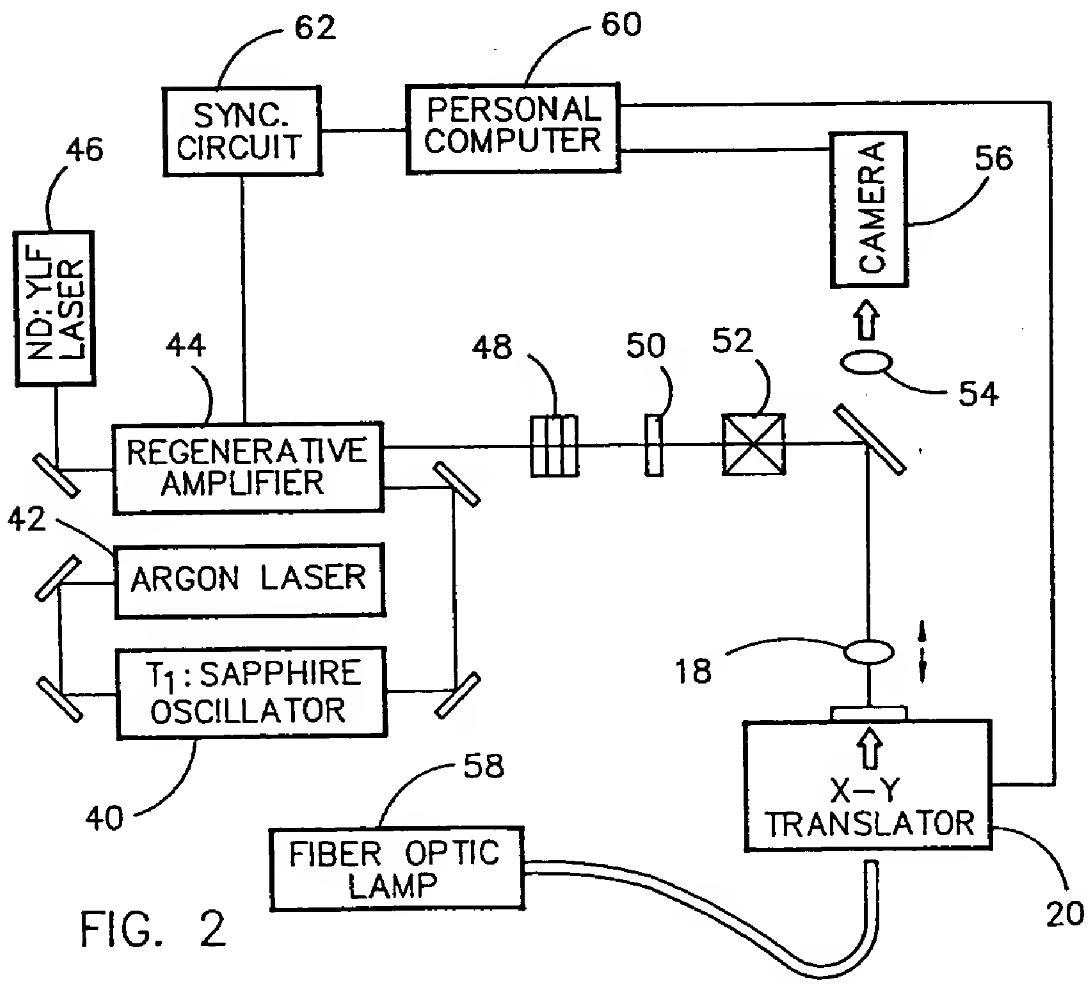
(e) condensing the evaporated coolant outside of the subsurface channels.

35. The method of claim 32 wherein the step of circulating the through the subsurface channels comprises a step selected from the group consisting of providing a pressure differential to draw the coolant into the channels, using capillary action to draw the coolant into the channels, or a combination thereof.



FEMTOSECOND LASER
16
12
10
18
22
14
24
20

FIG. 1



62
60
SYNC. CIRCUIT
PERSONAL COMPUTER
46
CAMERA
56
ND:YLF LASER
44
48
50
52
54
REGENERATIVE AMPLIFIER
42
ARGON LASER
T_1:SAPPHIRE OSCILLATOR
18
40
58
X–Y TRANSLATOR
FIBER OPTIC LAMP
20

FIG. 2

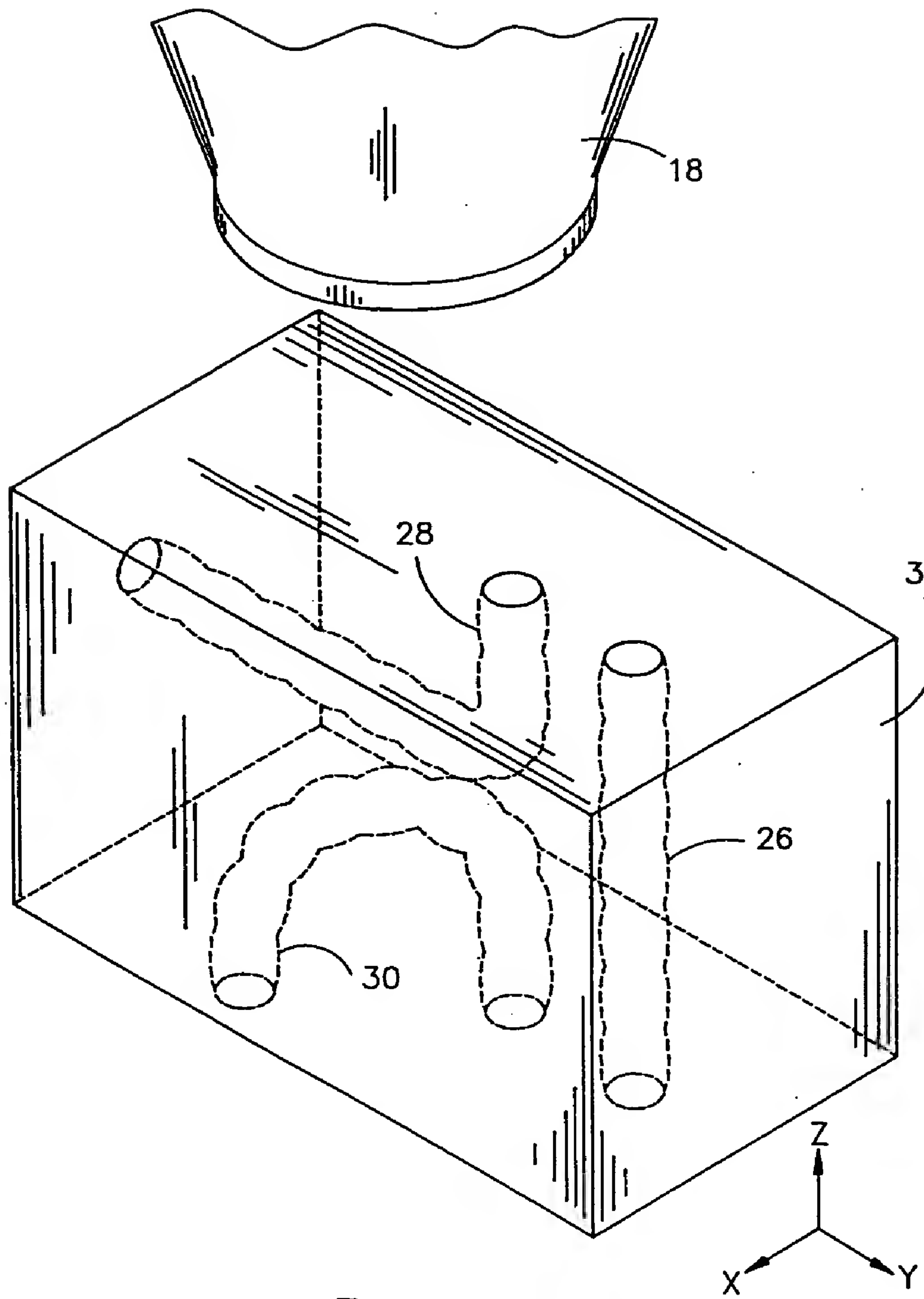


FIG. 3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/23835

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :B05D 3/06, 5/12; B32B 15/08; B23K 26/00
US CL :Please See Extra Sheet.
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : Please See Extra Sheet.

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

East (picosec, femtosec, attosec, etc.... with laser, width, pulse, pulsewidth; subclassess).

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,656,186 A (MOUROU et al) 12 August 1997 (12/08/97), see the abstract; Fig. 7-8; col. 1, lines 14-60; col. 2, lines 11-62; col. 3, lines 8-18 and 54-63; col. 4, lines 13-41; col. 7, line 1 - col. 8, line 7; col. 11, lines 31-34; and claims.	4-5, 9, 15-16, 23-25
Y	US 5,159,172 A (GOODMAN et al) 27 October 1992 (27/10/92), see the abstract; figures 2-3; col. 1, lines 5-47; col. 5, lines 30-68; and col. 7, lines 16-28 and 54-68.	4-5, 10-11, 15-16, 21-22, 23-25
X --- Y	US 5,349,155 A (YAMAGISHI et al) 20 September 1994 (20/09/94), see abstract; figrues; col. 1, lines 8-33; Summary; col. 5, lines 7-61; Ex. 1 on col. 6, lines 14-62.	1-3, 6, 12-14, 17-22, --- 4-5, 7-11, 15-16, 23- 25

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

08 DECEMBER 2000

Date of mailing of the international search report

12 JAN 2001

Name and mailing address of the ISA/US
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/23835

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
E, Y	US 6,117,706 A (YOSHIOKA et al) 12 September 2000 (12/09/00), see abstract; figures; col. 6, lines 4-10+ and 53-67; col. 7, lines 13-26+; col. 10, lines 18-67; col. 11, lines 48 - col. 12, line 4; and col.15, line 53 - col. 16, line 28.	1-25
X --- Y	US 4,915,981 A (TRASKOS et al) 10 April 1990 (10/04/90), see abstract; figures.	1-3, 6, 12- 14 ----------- 10-11, 17- 25
Y	US 4,960,613 A (COLE et al) 02 October 1990 (02/10/90), see abstract; figures; col. 1, lines 36-68; col. 2, lines 15-60; col. 3, lins 8-15; col. 5, lines 25-68+.	2-4, 6-8, 13-14, 17-19
Y	US 5,169,678 A (COLE et al) 08 December 1992 (08/12/92), see abstract; figures; col. 1, lines 14-45; co. 2, lines 8-55; col 9, lines 3-20.	1-2, 6, 10- 13, 17-18, 20-25
Y	US 5,683,758 A (EVANS et al) 04 November 1997, (04/11/97), see abstract; figures, col .3, lines 1-23; col. 4, lines 1-36 and claims.	1-3, 6, 12-14, 17-18, 23-25
X --- Y	US 5,576,073 A (KICKELHAIN) 19 November 1996 (19/11/96), see the abstract; figures; col. 3, line 65 - col. 4, line 32 and claims.	1-2, 6, 12-13, 17 ---------- 10-11, 18-25
X --- Y	US 4,508,749 A (BRANNON et al) 02 April 1985 (02.04.85), see abstract; figures; col.4, lines 15-68+; col. 5, lines 41-68; col. 6, lines 31-68; col. 7, line 21 - col. 8, lines 27 and 50 - col. 9, line 20.	1-2, 6, 12-13, 17 ---------- 10-11, 18-25

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/23835

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Please See Extra Sheet.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-25

Remark on Protest ☐ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/23835

A. CLASSIFICATION OF SUBJECT MATTER:
US CL :

427/555, 96, 97, 99; 216/18, 65; 428/457; 118/720; 219/121.68, 121.69, 121.7, 121.71, 121.75

B. FIELDS SEARCHED
Minimum documentation searched
Classification System: U.S.

427/555, 96, 97, 98, 99, 255.12, 252, 250, 253; 216/13, 17, 18, 65, 66; 428/457, 901; 118/715, 720; 219/121.68, 121.69, 121.7, 121.71, 121.75

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING
This ISA found multiple inventions as follows:

Group I, claim(s)1-25, drawn to method, product and apparatus for laser etching/ablating channels, then depositing conducive material therein for electrical interconnects.
Group II, claim(s) 26, drawn to a method of transmission using an optical/electrical interconnect.
Group III, claim(s) 28-35, drawn to integrated circuits with cooling channels and a method for making.

The inventions listed as Groups I, II & III do not relate to a single inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: group I concerns the technical feature of laser formed channels with conductive material deposited therein, while group II requires the presence of voids used for optical channels that are not present in either groups I or III. Group III requires channels to be used for cooling of the electrical circuit, which is a technical feature not required by either groups I or II.

Applicant was called on the telephone on 11/30/00 & 12/1/00 and advised that the above lack of unity was being made. On 12/4/00, William Breen, for applicants returned the calls and asked for the lack of unity to be mailed.